

# A New Method to Measure and Map the Gas Scale–Height of Disk Galaxies

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## ABSTRACT

We propose a new method to measure and map the gas scale height of nearby disk galaxies. This method is applied successfully to the Australia Telescope Compact Array interferometric HI survey of the Large Magellanic Cloud (LMC); it could also be applied to a significant number of nearby disk galaxies, thanks to the next generation of interferometric facilities, such as the extended VLA and CARMA.

The method consists of computing the Spectral Correlation Function (SCF) for a spectral–line map of a face–on galaxy. The SCF quantifies the correlation between spectra at different map positions as a function of their separation, and is sensitive to the properties of both the gas mass distribution and the gas velocity field. It is likely that spatial correlation properties of the gas density and velocity fields in a galactic disk are sensitive to the value of the scale height of the gas disk. A scale–free turbulent cascade is unlikely to extend to scales much larger than the disk scale height, as the disk dynamics on those larger scales should be dominated by two dimensional motions.

We find a clear feature in the SCF of the LMC HI disk, on the scale of  $\approx 180$  pc, which we identify as the disk scale height. We are also tentatively able to map variations of the scale height over the disk.

*Subject headings:* turbulence – ISM: kinematics and dynamics – radio astronomy: interstellar: lines

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## 1. Introduction

The gas scale height of galactic disks is an important quantity related to the process of star formation. It can be used to constrain the surface density of matter, the balance between star formation processes and gravity, and the ISM pressure, which must be important for regulating star formation.

Optical images of edge-on galaxies show that the scale height of stellar disks are independent of position along their major axis (Van der Kruit & Searle 1981, 1982; Kylafis & Bahcall 1987; Shaw and Gilmore 1990; Barnaby & Thronson 1992), or slowly increasing with radius (de Grijs & Peletier 1997). The constancy of the stellar scale height must be related to the radial and vertical distribution of the gas, since molecular clouds (MCs) are responsible for both the formation of stars and the dynamical heating of the stellar disk (Spitzer & Schwarzschild 1951).

The vertical distribution of neutral hydrogen in our Galaxy has been studied by many authors. It is found that the HI scale height  $h$  is approximately constant over a large range of galactocentric radii (Dickey & Lockman 1990; Heiles 1991). It is commonly assumed that the HI gas is supported in the Galactic gravitational potential primarily by turbulence (Lockman & Gehman 1991), with contributions from magnetic and cosmic ray pressure (Parker 1966; Spitzer 1990) and radiation (Ferrara 1993).

The constancy of the gas scale height in galactic disks is a common assumption in several models. However, it should not be taken for granted, since direct measurements of the HI scale height in external galaxies are difficult and sparse, and the HI scale height has never been mapped in a face-on galaxy. A nearby edge-on galaxy where the HI distribution has been studied with very high linear resolution is NGC 891. Sancisi & Allen (1979) found the HI disk of NGC 891 to be less than 1 kpc thick near the center, increasing outwards up to 1–2 kpc. The HI disk flare is not confirmed in the later study by Swaters, Sancisi & van der Hulst (1997), where a significant HI halo component is instead identified, and it is pointed out that the inferred HI vertical density profile is dependent on the adopted kinematic model. The CO scale height for the same galaxy ( $\approx 220$  pc) has also been estimated (Scoville et al. 1993).

In this Letter we propose a new method to measure and map the HI scale height of face-on galaxies. The method is based on the application of the

Spectral Correlation Function (SCF) to HI interferometric surveys. The SCF (Rosolowsky et al. 1999; Padoan, Rosolowsky & Goodman 2001) quantifies the correlation between spectra at different map positions as a function of their separation, and is sensitive to the properties of both the gas mass distribution and the gas velocity field. The scale corresponding to the scale height of the HI disk should mark the transition from small-scale three-dimensional turbulence to two-dimensional large-scale motions on the disk, since the ratio between radius and scale height of the cold gas in typical disk galaxies is very large ( $\sim 100$ ). This transition should appear as a feature in the SCF at a spatial lag approximately equal to the HI scale height. On smaller scales the SCF should instead be a power law reflecting the self-similar nature of turbulence, as in MCs (Padoan, Rosolowsky & Goodman 2001).

We have applied this method to the Australia Telescope Compact Array (ATCA) interferometric HI survey of the Large Magellanic Cloud (LMC) by Kim et al. (1998a,b, 1999), combined with the single dish survey done with the Parkes Multibeam by Staveley-Smith et al. (in preparation). Results of the combined survey are presented in Kim et al. (in preparation – see also astro-ph/0009299). We find that the SCF is indeed a power law on small scale, and has a characteristic feature at approximately 180 pc, where the power law is interrupted. We identify the scale of the clear “break” in the SCF as the HI scale height. We are also able to map significant variations of the scale height over the disk, between  $\approx 140$  and 240 pc.

In a recent work, Elmegreen, Kim & Staveley-Smith (2001) have computed the power spectrum of HI intensity maps of the LMC from the same survey used in this work. They find that the power spectrum of intensity is steeper on small scales than on large ones. The transition occurs at approximately 80–100 pc, and is interpreted as the line of sight thickness of the cold HI layer. The present Letter is qualitatively a confirmation of this earlier result, in the sense that both works show the possibility of using the statistical information from HI interferometric surveys to estimate the HI scale height of a face-on galaxy.

## 2. The SCF Method

The Spectral Correlation Function (SCF) measures the correlation between spectra at different map po-

sitions as a function of their spatial separation, and is sensitive to the properties of the gas mass distribution and the gas velocity field (Rosolowsky et al. 1999; Padoan, Rosolowsky & Goodman 2001).

Let  $T(\mathbf{r}, v)$  be the antenna temperature as a function of velocity channel  $v$  at map position  $\mathbf{r}$ . The SCF for spectra with spatial separation  $\Delta r$  is:

$$S_0(\Delta r) = \left\langle \frac{S_0(\mathbf{r}, \Delta r)}{S_{0,N}(\mathbf{r})} \right\rangle_{\mathbf{r}}, \quad (1)$$

where the average is done over all map positions  $\mathbf{r}$ .  $S_0(\mathbf{r}, \Delta r)$  is the SCF uncorrected for the effects of noise,

$$S_0(\mathbf{r}, \Delta r) = \left\langle 1 - \sqrt{\frac{\sum_v [T(\mathbf{r}, v) - T(\mathbf{r} + \Delta \mathbf{r}, v)]^2}{\sum_v T(\mathbf{r}, v)^2 + \sum_v T(\mathbf{r} + \Delta \mathbf{r}, v)^2}} \right\rangle_{\Delta \mathbf{r}}, \quad (2)$$

where the average is limited to separation vectors  $\Delta \mathbf{r}$  with  $|\Delta \mathbf{r}| = \Delta r$ , and  $S_{0,N}(\mathbf{r})$  is the SCF due entirely to noise,

$$S_{0,N}(\mathbf{r}) = 1 - \frac{1}{Q(\mathbf{r})}, \quad (3)$$

and  $Q(\mathbf{r})$  is the “spectrum quality” (see discussion in Padoan, Rosolowsky & Goodman 2001).  $Q(\mathbf{r})$  is computed as the ratio of the rms signal within a velocity window  $W$  to the rms noise,  $N$ ,

$$Q(\mathbf{r}) = \frac{1}{N} \sqrt{\frac{\sum_v T(\mathbf{r}, v)^2 dv}{W}}, \quad (4)$$

where  $dv$  is the width of the velocity channels.

The SCF has been computed for both molecular cloud data and synthetic data obtained by solving the radiative transfer through the three-dimensional density and velocity fields of numerical simulations of super-sonic MHD turbulence. The result is typically a power law that extends up to a separation  $\Delta r$  comparable to the map size, reflecting the self-similarity of super-sonic turbulence (see Padoan, Rosolowsky & Goodman 2001, and references therein).

### 3. The SCF and the Scale-Height of the LMC HI Disk

We have computed the SCF for several regions of the Australia Telescope Compact Array (ATCA) interferometric HI survey of the Large Magellanic Cloud (LMC) by Kim et al. (1998a,b, 1999), combined with the single dish survey done with the Parkes Multi-beam by Staveley-Smith et al. (in preparation). The

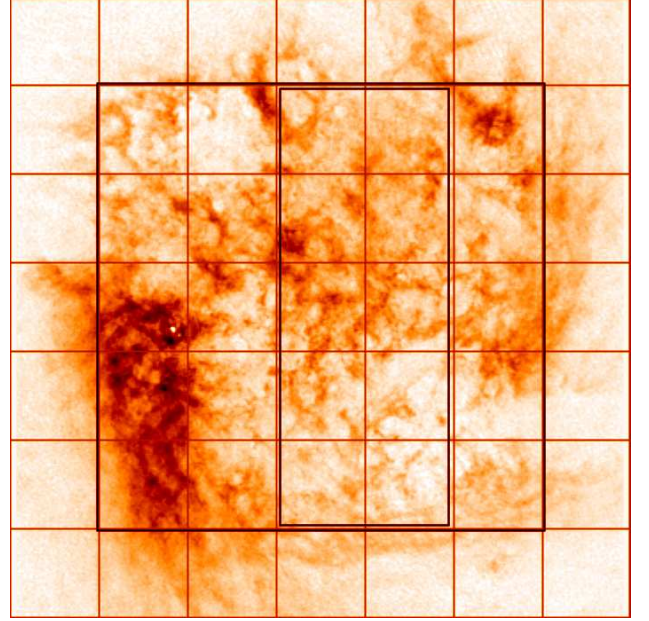


Fig. 1.— Velocity integrated HI intensity in the LMC from the ATCA interferometric survey by Kim et al. (1998a,b, 1999), combined with the single dish survey done with the Parkes Multibeam by Staveley-Smith et al. (in preparation). The perimeter of each of the 25 regions used to compute the SCF is over-plotted.

original data has been rebinned to a resolution of  $80''$ , that is a linear resolution of 20 pc assuming a distance to the LMC of 50 kpc (Feast 1991). We therefore obtain a map made of  $350 \times 350$  spectra ( $7 \times 7$  kpc), with 120 velocity channels. The velocity resolution is 1.65 km/s. Details about the ATCA survey can be found in Kim et al. (1998a,b, 1999).

The finite size of a map with non-periodic boundaries generates edge effects in correlation functions. In order to avoid this problem, we have computed the SCF for subsets of  $50 \times 50$  spectra ( $1 \times 1$  kpc), excluding the data from the “edges” of the map. The spectra in each subset have been compared with all spectra within a larger area around that subset, including  $150 \times 150$  spectra ( $3 \times 3$  kpc). In this way the SCF for all the spectra in each subset can be computed up to a separation equal to the size of the subset (1 kpc), without any effects related to the finite size of the map.

Figure 1 shows the integrated HI intensity map of the LMC, divided into  $7 \times 7$  subsets with  $50 \times 50$  spectra each. The SCF has been computed only for the

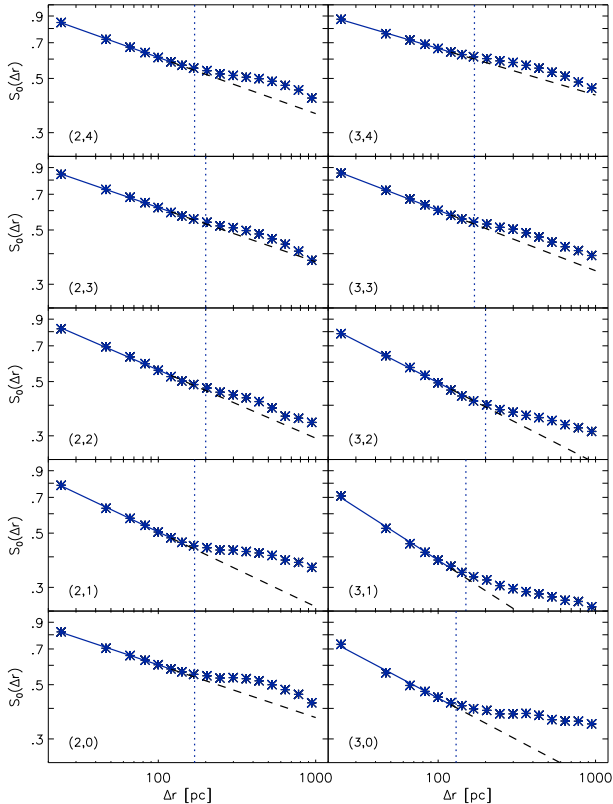


Fig. 2.— The SCF for the third and fourth column of regions from Figure 1. The regions are given coordinates  $(x,y)$  starting from  $(0,0)$  at the bottom left corner of the  $5 \times 5$  square in Figure 1.

$5 \times 5$  central ones (delimited by the darker square) for which complete sets of  $150 \times 150$  reference spectra are available. For lack of space, we have plotted in Figure 2 only the SCF computed inside the area marked with the rectangle in Figure 1.

Figure 2 shows that the SCF is a power law on small scales over almost an order of magnitude range in spectral separation  $\Delta r$ . The power law slope of the SCF varies from  $-0.40$  to  $-0.15$  over the whole map. The power law is very clearly interrupted at  $\approx 180$  pc, where the slope of the SCF generally decreases. In 22 of the 25 regions, the SCF breaks to a “shallower” slope on larger scales. It sometimes becomes steeper again on the scale of a few hundred pc, due probably to the effect of differential rotation, which grows with increasing spectral separation. In only 3 of the 25 cases, the SCF breaks from a power law to a “steeper” slope. This happens in the 3 regions around the lo-

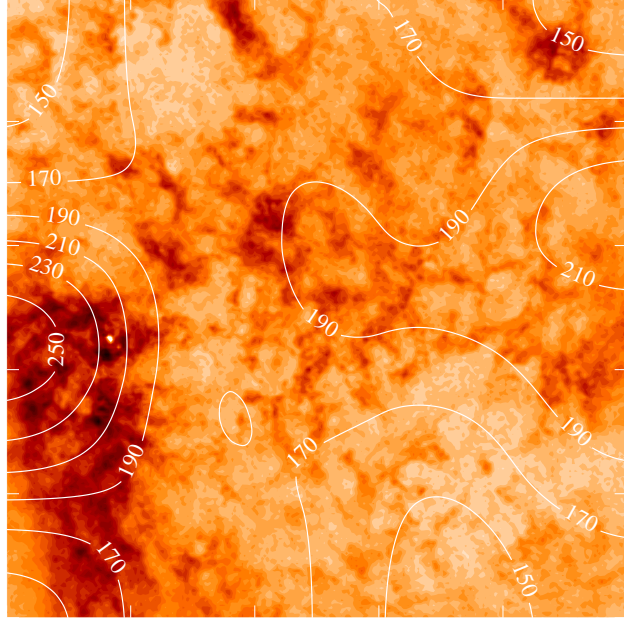


Fig. 3.— Contour map of the SCF scale height of the LMC disk. Values of contour lines are in pc. The intensity map shows the HI integrated intensity as in Figure 1.

cation of 30 Doradus, and south of it (the 3 regions covering the largest intensity feature on the bottom left of the map in Figure 1).

We interpret the interruption of the power law shape of the SCF as the outer scale of three dimensional super-sonic turbulence in the LMC disk. A scale-free cascade of three dimensional turbulence is unlikely to extend to scales much larger than the disk scale height, as virtually two dimensional flows should dominate the dynamics on those larger scales. The power law shape of the SCF for the HI data reflects the presence of self-similar turbulence, probably extending to much smaller scale than probed by the present survey (20 pc in our rebinned data). Below 20 pc the turbulent cascade is well-probed by the SCF of molecular emission line maps (see Padoan, Rosolowsky & Goodman 2001).

Assuming that the the SCF is indeed sensitive to the HI scale height,  $h$ , we find that  $h$  varies in the range  $130 < h < 280$  pc over the surveyed area. The largest value is found in the region around 30 Doradus. Statistical error bars are smaller than the size of the symbols used in the plots in Figure 2, and variations of  $h$  are therefore significant. Figure 3 shows

a contour map of  $h$  over the  $5 \times 5$  regions where the SCF has been computed. The average value is  $\langle h \rangle \approx 176$  pc. Kim et al. (1999) estimated the HI scale height using the average vertical velocity dispersion and the average surface density of both the HI and the stellar components of the LMC disk, and adopting the disk model by Dopita & Ryder (1994). They found  $h \approx 180$  pc. This is almost identical to the value of  $\langle h \rangle$  estimated with the SCF method, which is the main reason why we interpret the outer correlation scale of the SCF as the local value of the disk scale height. Nevertheless, we cannot rule out possible alternative interpretations of the SCF results, and the subject deserves further study.

Elmegreen, Kim & Staveley-Smith (2001) have recently computed the power spectrum of HI intensity maps of the LMC obtained with data from the same survey used in this work. They find a steeper power spectrum on small scales than on large ones. The transition occurs at approximately 80–100 pc, and is interpreted as the line of sight thickness of the HI layer, based the theoretical results by Lazarian & Pogosian (2000).

In this work we confirm the possibility of using the statistical information from HI interferometric surveys to estimate the HI scale height of a face-on galaxy. However, there is a fundamental difference between the present Letter and the work by Elmegreen, Kim & Staveley-Smith (2001), apart from the different method of data analysis adopted. Elmegreen, Kim & Staveley-Smith (2001) implicitly assume that the three dimensional power spectrum of the turbulent density field is described by a unique power law over all scales, and the change in slope of the two dimensional power spectrum of integrated intensity is merely a projection effect. Here instead we argue that there must be a physical transition in the statistical properties of the flow on a scale close to the disk scale height, which the SCF is sensitive to.

#### 4. Conclusions

We have proposed a new way to measure and map the scale height of the gas in face-on disk galaxies, based on the application of the SCF to HI interferometric surveys. We have shown that this method applies successfully to the LMC. It can be applied to a number of nearby galaxies, depending on the spatial and velocity resolution of HI or molecular transition interferometric surveys. The BIMA survey of nearby

galaxies, BIMA SONG (Regan et al. 2001), for example, has an angular resolution of approximately  $6''$  (using the D and C array configurations), and can achieve approximately  $3''$ , with the B array configuration. At the distance of 4 Mpc, a  $3''$  resolution corresponds to a linear resolution of  $\approx 60$  pc. There are six galaxies within the approximate distance range between 2 and 4.5 Mpc, in the BIMA SONG list: IC0342, NGC2403, NGC2976, NGC3031, NGC4736 and NGC4826. They could in principle be studied with this method. Problems with the CO surveys may arise due to the low surface filling factor of CO relative to HI, and, in the particular case of the BIMA SONG survey, due to the relatively low velocity resolution (4.06 km/s). However, a velocity resolution of approximately 1.0 km/s could be easily achieved with BIMA in these galaxies (Tamara T. Helfer, private communication).

For 21-cm HI observations, a 50-km baseline in a radio interferometer gives a resolution of 16 pc at 4 Mpc. At 3-mm, CO gives the same kind of resolution on a 0.7-km baseline. Therefore, the synthesized beams of the immediate descendants of existing cm and mm interferometers (e.g. the EVLA and CARMA) should be able to map many galaxies with more-than-adequate resolution for the SCF to be used to measure, and map out, galactic scale height.

The application of this method to a number of galaxies could provide new important measurements of the gas scale height and its variations inside individual disks and between different galaxies. Once the scale height is measured, it can also be used, together with the observed vertical velocity dispersion, to put new constraints on the distribution of dynamical mass in galactic disks.

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